HYPERNOVA NUCLEOSYNTHESIS AND IMPLICATIONS FOR COSMIC CHEMICAL EVOLUTION

TAKAYOSHI NAKAMURA[1], HIDEYUKI UMEDA[1], KOICHI IWAMOTO[2], KEN'ICHI NOMOTO[1], MASA-AKI HASHIMOTO[3], W. RAPHAEL HIX[4], AND FRIEDRICH-KARL THIELEMANN[5]

[1] *Department of Astronomy, School of Science, University of Tokyo, Tokyo, Japan*
[2] *Dept. of Physics, College of Science and Technology, Nihon Univ., Tokyo, Japan*
[3] *Department of Physics, School of Sciences, University of Kyushu, Fukuoka, Japan*
[4] *Department of Physics and Astronomy, University of Tennessee, Knoxville, TN and Physics Division, Oak Ridge National Laboratory, Oak Ridge, TN, USA*
[5] *Department für Physik und Astronomie, Universität Basel, Switzerland*

We examine the characteristics of nucleosynthesis in 'hypernovae', i.e., supernovae with very large explosion energies ($\gtrsim 10^{52}$ ergs). Implications for the cosmic chemical evolution and the abundances in M82 are discussed.

1 Enhancement of [Fe/O], [Ti/O], and [Si, S/O]

The explosion energy of SN1998bw is estimated to be $E = 3$ - 6×10^{52} ergs, which is about thirty times larger than that of a normal supernova (Iwamoto et al. 1998; Woosley et al. 1999; Nakamura et al. 2001). We explore nucleosynthesis in such energetic core-collapse supernovae, called 'hypernovae' (Nakamura et al. 2000), and find the following characteristics. In hypernovae, both complete and incomplete Si-burning take place in more extended, and hence, lower density regions, so that the α-rich freezeout is enhanced in comparison with normal supernova nucleosynthesis. Thus ^{44}Ca ($\leftarrow$ ^{44}Ti) and ^{48}Ti are produced more abundantly than in canonical supernovae. Oxygen and carbon burning also takes place in more extended regions for the larger explosion energy. Therefore, the fuel elements O, C, Al are less abundant while a larger amount of burning products such as Si, S, and Ar are synthesized by oxygen burning. In short, [Ti/O] and [Si, S, Ar/O] as well as [Fe/O] are enhanced in hypernovae.

2 Comparison with abundances in metal-poor stars

Ti is known to be deficient in Galactic chemical evolution models that use supernova yields currently available (e.g., Timmes et al. 1995; Thielemann et al. 1996), especially at [Fe/H] $\lesssim -1$, when Type Ia supernovae (SNe Ia) have not contributed to the Galactic chemical evolution. However, if the contribution from hypernovae is relatively large, this problem could be relaxed, because, as we have seen, the α-rich freezeout is enhanced in hypernovae and Ti is produced more abundantly than normal supernovae.

Another feature of hypernova nucleosynthesis is a large amount of Fe. One hypernova can produce 2 - 10 times more Fe than normal core-collapse supernovae. This large iron production leads to small ratios of α-elements over iron in hypernovae. In this connection, the abundance pattern of the very metal-poor binary CS22873-139 ([Fe/H] $= -3.4$) is interesting. This binary has only an upper limit to [Sr/Fe] < -1.5, and therefore was suggested to be a second generation star (Nordström et al. 2000; Spite et al. 2000). The interesting pattern is that this binary shows almost solar Mg/Fe and Ca/Fe ratios, as is the case with hypernovae. Another feature of CS22873-139 is enhanced Ti/Fe ([Ti/Fe] $\sim +0.6$; Nordström et al. 2000; Spite et al. 2000), which could be explained by a hypernova explosion.

3 Abundances in the starburst galaxy M82

X-ray emissions from the starburst galaxy M82 were observed with ASCA and the abundances of several heavy elements were measured (Tsuru et al. 1997). Tsuru et al. (1997) found that the overall metallicity of M82 is quite low, i.e., O/H and Fe/H are only 0.06 - 0.05 times solar, while Si/H and S/H are $\sim$ 0.40 - 0.47 times solar. This implies that the abundance ratios are peculiar, i.e., the ratio O/Fe is about solar, while the ratios of Si and S relative to O and Fe are as high as $\sim$ 6 - 8. These ratios are very different from those ratios in Type II supernovae (SNe II). The age of M82 is estimated to be $\lesssim 10^8$ years, which is too young for SNe Ia to contribute to enhance Fe relative to O. Tsuru et al. (1997) also estimated that the explosion energy required to produce the observed amount of hot plasma per oxygen mass is significantly larger than that of normal SNe II (here the oxygen mass dominates the total mass of the heavy elements). Tsuru et al. (1997) thus concluded that neither SN Ia nor SN II can reproduce the observed abundance pattern of M82.

Compared with normal SNe II, the important characteristic of hypernova nucleosynthesis is the large Si/O, S/O, and Fe/O ratios. Figure 1 shows the good agreement between the hypernova model and the observed abundances in M82 (Umeda et al. 2001). Hypernovae could also produce larger E per oxygen mass than normal SNe II. We therefore suggest that hypernova explosions may make important contributions to the metal enrichment and energy input to the interstellar matter in M82. If the IMF of the star burst is relatively flat compared with Salpeter IMF, the contribution of very massive stars and thus hypernovae could be much larger than in our Galaxy.

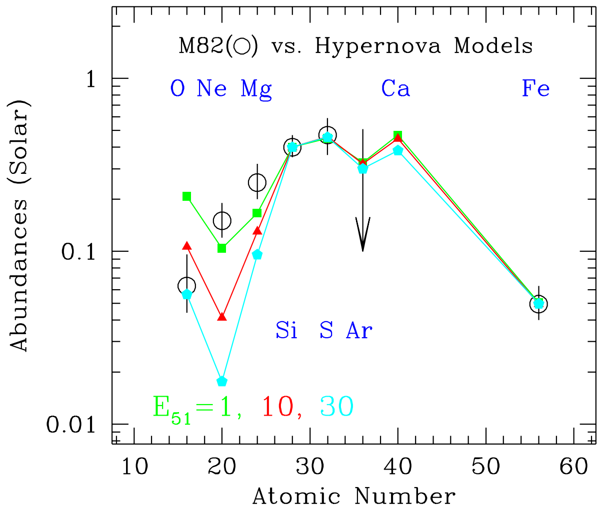

Figure 1. Abundance patterns in the ejecta of $25M_\odot$ metal-free SN II and hypernova models compared with abundances (relative to the solar values) of M82 observed with ASCA (Tsuru et al. 1997). Here, the open circles with error bars show the M82 data. The filled square, triangle, and pentagons represent E_{51}=1, 10, and 30 models, respectively, where E_{51} is the explosion energy in 10^{51} ergs. Theoretical abundances are normalized to the observed Si data, and the mass cuts are chosen to eject 0.07, 0.095, and 0.12 ($M_\odot$) Fe for E_{51} = 1, 10, and 30, respectively (Umeda et al. 2001).

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